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FINAL PROJECT REPORT

ADVANCED THERMO-ELECTRIC GENERATOR SYSTEM (ATEGS)

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Advanced Thermo-Electric Generator System (ATEGS) is the final report for Contract Number PIR-17-002 conducted by Altex Technologies Corporation and Hi-Z Technology, Inc. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Thermo-electric generators (TEG) can generate power from process waste heat and reduce fuel use and cost, criteria pollutants, and greenhouse gases. However, these systems have low efficiencies that hinder cost-effectiveness. Increasing TEG efficiency will make these systems more competitive. This project explored how the Advanced Thermo-electric Generator System (ATEGS) can exceed five percent efficiency and also have a payback time of fewer than five years. To meet these goals, high-temperature lead telluride (PbTe) and low-temperature bismuth telluride (BiTe) modules were fabricated, integrated into systems, and tested in an available boiler/heater to demonstrate ATEGS efficiencies at high and low temperatures. The high-temperature PbTe modules exceeded an efficiency of five percent, with a payback of 6.27 years. The low-temperature BiTe module payback was 4.77 years, which meets the project target. The high- and low-exhaust temperature combined heat and power systems had low paybacks of 1.00 and 0.56 years, respectively.

Keywords: Advanced Thermo-Electric Generator System, ATEGS, power generation, heat to electric power, waste heat, industrial sector, combined heat and power, CHP

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Executive Summary

Many fuel-based commercial and light-industrial processes generate waste heat that is discharged to the atmosphere without secondary benefits. This waste heat could be used to generate power (and hot water, in some options), increase overall system efficiency, and decrease fuel consumption, fuel costs, and criteria air pollutants and greenhouse gas emissions. Furthermore, by generating power, the waste heat system can increase system resiliency during grid outages. To realize these benefits, a solid-state-based Advanced Thermo-electric Generator System (ATEGS) was developed and tested at sub-scale to demonstrate its ability to generate power and hot water from waste heat at lower temperatures of up to 500 degrees Fahrenheit (°F) (260 degrees Celsius [°C]), as well as at higher temperatures of up to 1040°F (560°C). By developing a low- and high-temperature ATEGS, a broad range of waste heat applications, including boilers, heaters, engines, gas turbines, and metal, glass, and ceramic furnaces, would benefit. Developing and commercializing an ATEGS will support ratepayers under Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006) by making cost-effective waste heat to power and distributed generation systems available for California industries.

ATEGS power generation is based on the thermo-electric effect, which is the direct conversion of heat to electric power, and it uses materials known as semiconductor thermo-electric materials. The process would require effective heat exchangers for transferring heat from the hot waste heat gases to one side of the thermo-electric generator (TEG), and from the other side of the TEG to the cooling water. This cooling water can be further heated using the remaining waste heat gases and used for hot water needs at commercial or industrial sites, thereby expanding the benefits of the system beyond power generation.

Project Purpose and Approach

The major goals and objectives of this project were to develop pilot-scale ATEGS prototype test articles and execute validation and demonstration tests to determine system performance and cost competitiveness for broad waste heat applications of interest to the state of California. The demonstrations were to integrate and test low-cost, high- and low-temperature ATEGS to show that renewable power efficiency can be greater than 5 percent for some waste heat applications, with a payback of less than 5 years and over a 10-year lifetime.

To accomplish these goals, researchers used state-of-the-art high-temperature, and commercial low-temperature, TEG modules with advanced heat exchangers to create the ATEGS. Power was the primary output, with some applications also producing hot water in a retrofittable system. Facilities such as food processing and chemicals processing could potentially generate up to 22 percent of their power and additionally process hot water.

High-temperature ATEGS were constructed with TEG modules composed of segmented semiconductor elements made of lead telluride (PbTe) and bismuth telluride (BiTe), and the low-temperature ATEGS were constructed from BiTe TEG modules. To reduce payback times, high- and low-temperature ATEGS were integrated with ancillary heat exchangers to produce hot water in the combined heat and power option. Test data and simple cost estimation results were used to project the economic and environmental benefits of using high- and low-temperature ATEGS.

Key Results

Low-temperature ATEGS

Initial tests using temperatures up to 500°F (260°C) showed that module loading was constrained by the packaging, which increased interface thermal resistance and reduced power output and efficiency. Reducing loading constraints also reduced interfacial thermal resistance and significantly improved power output and efficiency. Some constraints remained, however, and the maximum efficiency was only approximately 3 percent, which is below the project objective of greater than 5 percent. It is unlikely that BiTe-based ATEGS will exceed the 5-percent project efficiency target.

High-temperature ATEGS

Results showed that using 914°F (490°C) is low for power output and good for longevity; 1040°F (560°C) gives a reasonable power output with reasonable longevity; 1112°F (600°C) is possibly high for longevity. Only long-term testing will show the longevity capability. In this case, the module loading constraints were reduced, and power output exceeded that of the low-temperature system. However, the power output of the ATEGS, which was limited by the test system, still fell short of the individual TEG module tests by up to 40 percent at an equivalent temperature. High-temperature module test results showed that they could exceed the 5-percent efficiency project objective. It is anticipated that a properly insulated, high-temperature system would also exceed 5-percent efficiency.

Payback Timeframe

Using test results and component, assembly, and installation estimated costs, high- and low-temperature ATEGS costs were estimated with and without hot water production. The low-temperature system had a payback of 4.77 years, and the high-temperature system had a payback of 6.27 years. The low-temperature system meets the under-5-year project objective. However, by including the hot water from the combined heat and power option, the high- and low-temperature systems have paybacks of 1.00 year and 0.56 years, respectively, which easily meet the under-5-year payback project objective.

Emissions Reductions

Considering full deployment as 20-percent deployment in the full market, which represents 6,250 low-temperature and 4,375 high-temperature 8-kilowatt electric ATEGS applications in California, oxides of nitrogen criteria pollutants and carbon dioxide greenhouse gases would be reduced by 33.2 tons per year and 255,000 tons per year, respectively. For the ATEGS using combined heat and power options, the projected reductions are 261.5 tons per year and 3,572,500 tons per year, respectively. Relative to overall boiler and heater emissions, these ATEGS reductions are 1.1 percent and 22.3 percent for the baseline and the combined heat and power ATEGS options, respectively. The full deployment cost to industry users is $649 million for ATEGS and $867 million for ATEGS using combined heat and power options.

Knowledge Transfer and Next Steps

The cost analysis concluded that the ATEGS is cost effective and environmentally beneficial for low-temperature waste heat and for low- and high-waste heat temperatures if the combined heat and power option is used. However, while the potential is clear, test systems and the overall project had some challenges that must be resolved to realize the full potential of the ATEGS. For example, the thermal resistances were excessive at the interface between the heat exchanger and module. To correct this problem and optimize performance, the interface should be smoothed out and have uniform surface contact. Other challenges included COVID-19 pandemic-related disruptions, the loss of the host site, and schedule delays for the ATEGS testing. With all these challenges, and in the absence of available test data, no ATEGS publications were prepared or presented at conferences.

By implementing corrections for smoothness and interface contact, performance and costs will be improved, and knowledge transfer can be initiated for the systems. Relative to production readiness, the heat exchanger and packaging components are nearly ready for manufacture. The low-temperature modules are currently being manufactured at low-production volumes. The high-temperature modules are state-of-the-art, and more research into materials and fabrication processes and long-term durability testing is needed to demonstrate their cost-effectiveness and durability. Once this effort is completed, the technical knowledge transfer activities, including talks at conference presentations, showcasing conference posters, and publishing articles in peer-reviewed journals, production of the high-temperature module can be accomplished. For both the low- and the high-temperature modules, an investment in the manufacturing, tooling, and equipment would be required to increase production throughput and decrease costs. Specific to the high-temperature module, these efforts could be completed within three years.

CHAPTER 1: Introduction

The Need for ATEGS

Many commercial and light-industrial processes that use fuel generate waste heat that is discharged to the atmosphere without benefitting the site. If this waste heat could be used to generate power and hot water, then the overall system efficiency could be increased, reducing fuel use, cost, and criteria air pollutants and greenhouse gas (GHG) emissions. By generating power, the waste heat system can also increase system resiliency during grid outages. To realize the benefits of waste heat, a solid-state-based Advanced Thermo-electric Generator System (ATEGS) was developed and tested at sub-scale to demonstrate the ability of the system to generate power and hot water from different waste heat temperatures. These included lower temperatures of up to 500 degrees Fahrenheit (°F) (260 degrees Celsius [°C]), as well as higher temperatures of up to 1040°F (560°C). By developing both low- and high-temperature ATEGS, a broad range of waste heat applications and exhaust temperatures would benefit, including those listed in Table 1 (Elson et al., 2015). Moreover, ATEGS will support ratepayers under Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006) by making cost-effective waste heat to power and distributed generation systems available for California industries.

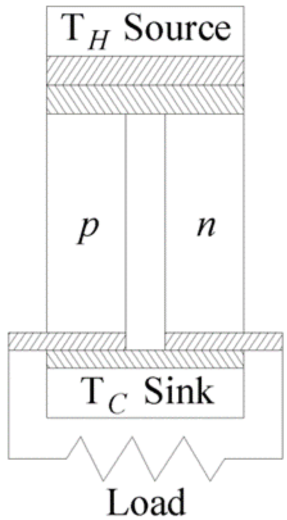
Table 1: ATEGS Waste Heat Applications

Applications	Temperature (°C)
Iron/Steel Making	982
Aluminum and Non-Ferrous Metal Making	704
Chemical	704
Cement Dry Kiln	449
Glass Melting Regenerative	427
Glass Melting Electric Boost	427
Chemical Manufacturing	441
Food Manufacturing	441
Oil and Gas	454
Cement Wet Kiln/Precalciner/Preheater	338
Boiler Conventional Fuels	260

Source: Elson et al., 2015

ATEGS power generation is based on the thermo-electric effect, which is the conversion of heat to electric power, and it occurs when using materials known as semiconductor thermo-electric materials. As illustrated in Figure 1, it works where one side of the P-type or N-type semiconductor thermo-electric material (for example, bismuth telluride [BiTe]) is pressed against a hot surface, denoted as hot-side Th, and the other is pressed against a cold surface, denoted as cold-side Tc. The result is that voltage is produced across the P and N material that can then generate a current when the two sides are part of an electric circuit. This process essentially converts the waste heat into electricity.

Figure 1: Basic Thermo-electric Generator Process



Source: Hi-Z Technology, 2023

Given the basic configuration shown in Figure 1, effective heat exchangers are needed to transfer heat from hot-waste heat gases to the hot side of the thermo-electric generator (TEG) and a heat exchanger on the low-temperature side of the TEG is needed to transfer heat to the cooling water. This cooling water can be further heated by the remaining waste heat and used for hot-water needs at the commercial or industrial site, expanding the benefits of the system beyond solely generating power.

The above description is simplistic, and ATEGS technology development, testing, and demonstration were required to show how this technology can be adapted to a broad range of waste heat applications at capital and operating costs that will drive adoption of the ATEGS for important waste heat markets in California. To achieve economic viability, system efficiency (power output versus heat required to produce the output) needs to be high enough to limit capital costs for heat-management components in the ATEGS. To meet this goal, the ATEGS developed in this project was assumed to require a power efficiency of over 5 percent. Conventional commercial BiTe TEG modules, when integrated into a system, cannot reach this level of efficiency. Higher operating temperature lead-telluride (PbTe)-based TEG modules can potentially reach 5-percent efficiency with hot-side upstream gas temperatures in the range of 932°F (500°C) to 1112°F (600°C).

To ensure reaching the target efficiency, the ATEGS developed in this project utilized the segmented element technique, where the high temperature PbTe-based segment interfaces with the hot-side heat exchanger that is heated by waste heat gases and attached to the low-temperature BiTe-based segment, which interfaces with the water-cooled cold-side heat sink.

This approach maximizes efficiency that exceeds 5 percent. Furthermore, for high waste heat gas temperatures, gases exiting the high-temperature thermo-electric generator (HTTEG) will still have significant energy and the low-temperature thermo-electric generator (LTTEG) unit, which has only BiTe-based elements, will be used to extract more energy and produce more power from waste heat gases.

The overall system is configured as:

ATEGS= (**system**)

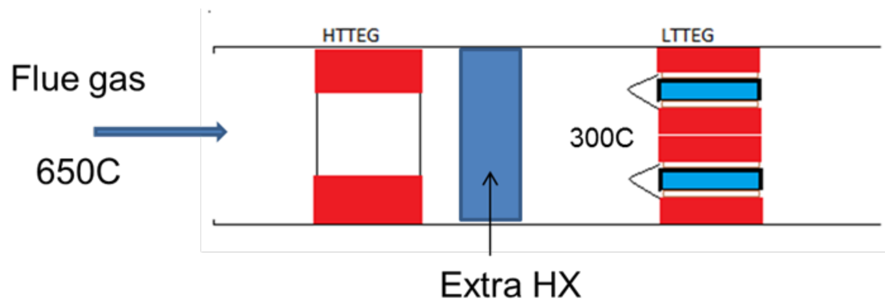
→ HTTEG and/or LTTEG **units**

→ (Segmented elements **technique**)

→ (BiTe or PbTe and BiTe) TEG **modules**

This segmentation is illustrated in Figure 2, which shows serially aligned HTTEG and LTTEG units for the high-temperature ATEGS. This ATEGS is segmented in two ways: PbTe-based and BiTe-based segmented elements for maximizing HTTEG efficiency, and BiTe-based elements for the LTTEG used downstream of the HTTEG to convert more of the high-temperature waste heat to electricity. Through this dual segmentation in ATEGS, the potential to achieve project objectives was increased.

Figure 2: ATEGS Segmented Configuration for the High-temperature Waste Heat Market



Source: Altex Technologies Corporation

ATEGS Potential Markets

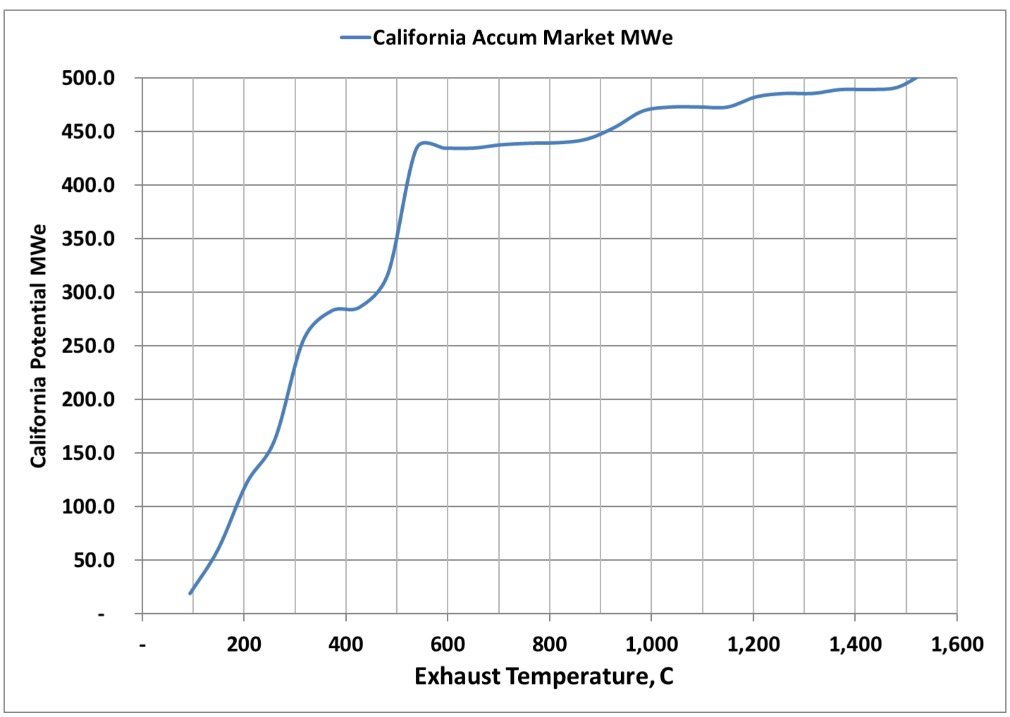
Table 1 shows the waste heat markets and exhaust temperatures that could be addressed by ATEGS. By developing HTTEG and LTTEG units, both high- and low-temperature markets can be addressed by ATEGS, with the high-temperature markets addressed with the segmented ATEGS solution illustrated in Figure 2. For the low-temperature markets, only the LTTEG unit would be utilized in ATEGS. Figure 3 shows the California potential waste heat market capacities as a function of waste heat gas temperature (Elson et al., 2015). As shown, the lower-temperature market, up to 600°F (316°C), is approximately one half of the total market. This market consists of commercial and light-industrial boilers and heaters. Potential specific applications include hospitals, hotels, schools, large office buildings, and food processing facilities. Twenty percent would be the estimated full deployment of LTTEG units, covering the 250-and-under megawatt electric (MWe) market shown in Figure 3 data at 600°F (316°C); 2.5

million 20-watt electric (We) BiTe TEG modules would be needed to support 6,250 LTTEG units, each with an 8-kilowatt electric (kWe) capacity. Assuming deployment over 10 years, the average production would be 250,000 BiTe TEG modules per year and 625 LTTEG units per year.

Applications between 600°F (316°C) and up to 1000°F (537.8°C) cover an additional 40 percent of the total market, which represents about 175 MWe. These applications, including engine exhaust and industrial processes (for example, metal, ceramic, and glass furnaces), would benefit from HTTEG units. At the higher temperatures, materials and designs would be upgraded to ensure reliability and longevity. Under the same deployment percentages and year assumptions as the LTTEG units, 1.75 million 20-We PbTe and BiTe modules would be needed to support 4,375 HTTEG units, each with an 8-kWe capacity, and average production would be 175,000 PbTe modules per year and 438 HTTEG units per year.

The very-high-temperature waste heat market, with temperatures above 1000°F (537.8°C) and up to 2700°F (1482.2°C), is only 10 percent of the market. In these cases, designs will be needed to protect the ATEGS from excessive heat to avoid both system degradation and efficiency reductions. In some cases, an air preheater heat exchanger and compatible burner could be implemented ahead of the ATEGS to moderate waste heat gas temperatures to optimal levels for the combined HTTEG plus LTTEG units, as illustrated in Figure 2. Given the extra challenge with this very-high-temperature waste heat market, the application of the ATEGS to this market is deferred until success is achieved in the more straightforward near-term market applications. Preliminary payback results indicate that the combined heat and power (CHP) option will have better paybacks for all temperature markets. This is discussed further in the section of this report titled Simple Cost Estimation Results.

Figure 3: California Waste Heat Markets



Source: Elson et al., 2015

Project Goals and Objectives

The goals of this project were to:

- Develop pilot-scale ATEGS prototype test articles and execute validation and demonstration tests to prove system performance and cost competitiveness for broad waste heat applications of interest to the state of California.
- Reduce facility operational costs by reducing grid power needs.
- Reduce facility GHG emissions and criteria pollutants.
- Support cost-competitive distributed generation technology implementation in the state of California and beyond.

When implemented in the waste heat markets, the ATEGS will result in the ratepayer benefits of greater electricity reliability, lower costs, and increased safety. This will be achieved by decreasing reliance on the grid, providing onsite electric power, improving thermal efficiency and fuel use when used in the CHP mode, reducing facility operational costs, reducing GHG and criteria pollutants, and reducing ratepayer costs.

This project was expected to lead to technological advancements to overcome barriers to achievement of California's statutory energy goals by using state-of-the-art high-temperature and low-temperature TEG modules, with advanced heat exchangers, to create ATEGS configurations that optimally address multiple waste heat markets with a competitive payback of under five years. Power was the primary useful output, with a CHP option of also producing hot water in a retrofittable system for the state's waste heat market.

The objectives of this project were to:

- Integrate low-cost, high- and low-temperature TEG modules with advanced heat exchangers and test the ATEGS to show that renewable power efficiency can be over 5 percent for some high-temperature waste heat applications in California.
- Show the durability of the ATEGS in a real and high-temperature application.
- Show that the ATEGS can recover over 80 percent of waste heat by producing hot water, reducing fuel use and cost, criteria pollutants, and GHG.
- Show that the ATEGS has a simple payback of fewer than five years and that the system is cost competitive.
- Show that, at full market penetration, the ATEGS can save hundreds of millions of dollars and reduce GHG emissions by nearly a million tons per year.
- Show that the ATEGS footprint is compatible with typical boiler installations.

CHAPTER 2: Project Approach

In support of this project, researchers teamed up with Hi-Z Technology, Inc. and received input from a technical advisory committee of consultants in the mechanical engineering, combustion and heat transfer equipment, and TEG fields. Hi-Z provided the TEG modules and worked on the high-temperature module development and testing. The researchers provided the heat exchanger technology and supported both the building and the testing of the ATEGS. Hi-Z has commercialized a low-temperature BiTe TEG module, which supported the LTTEG unit. The high-temperature PbTe and BiTe TEG modules were required to support the development of the HTTEG unit.

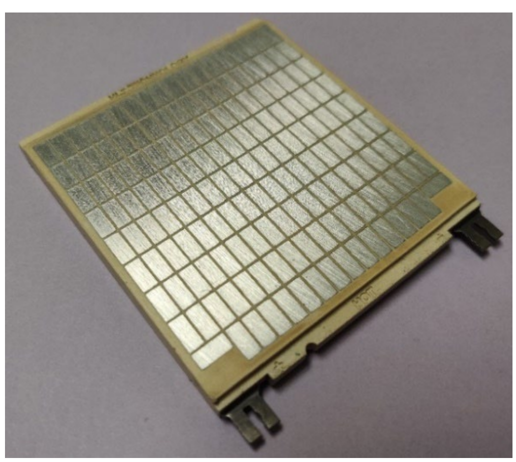
ATEGS Application Integration

For application and manufacturing requirements, TEG modules are commonly produced in standard sizes, voltages, and power ratings, with specific hot- and cold-side temperatures for best performance. To create a waste heat power system, multiple standard modules must be integrated into a system that recovers heat from the waste heat site.

LTTEG Unit Modules

The LTTEG unit used low-temperature modules supplied by Hi-Z. These are commercial BiTe HZ-20HV (high voltage) modules suitable for lower waste heat temperature applications like boilers (Hi-Z Technology, 2023). These modules contain thermo-electric semiconductor elements constructed of P and N types of BiTe materials. The P and N element pairs are wired in series to produce a typical open circuit voltage that is approximately equal to (~) 10 volts, with over 20 watts of power output to an impedance matched load. Figure 4 shows the HZ-20HV module, whose dimensions are 74.5 millimeters (mm) by 68mm by 5mm.

Figure 4: Low-temperature Hi-Z-20HV Commercial TEG Module



Source: Hi-Z Technology

Each module was individually tested before shipment and certified to produce over 20 watts at 482°F (250°C) hot-side and 122°F (50°C) cold-side temperatures. Specifications for the modules are shown in Table 2 (Hi-Z Technology, 2023). The modules used in the LTTEG unit are illustrated here.

Table 2: LTTEG Unit (HZ-20HV) Module Specifications

Estimated Thermal and Electrical Characteristics					
Parameter	**Conditions**	**Min**	**Typical**	**Max**	**Unit**
Power	Th=482°F (250°C), Tc=122°F (50°C) @matched load	23.1	24.3	25.5	W
Open Circuit Voltage	Th=482°F (250°C), Tc=122°F (50°C)	10.3	10.8	11.3	V
Matched Load Voltage	Th=482°F (250°C), Tc=122°F (50°C)	5.2	5.4	5.6	V
Internal Resistance	Th=482°F (250°C), Tc=122°F (50°C)	1.14	1.2	1.26	Ω
	Th = Tc = 77°F (25°C)	0.73	0.77	0.81	Ω
Current	Th=482°F (250°C), Tc=122°F (50°C) @matched load	4.3	4.5	4.7	A
	Th=482°F (250°C), Tc=122°F (50°C) @short circuit	8.5	9.0	9.5	A
Heat Flow	Th=482°F (250°C), Tc=122°F (50°C) @matched load	703	740	777	W
	Th=482°F (250°C), Tc=122°F (50°C) @open circuit	570	600	630	W
Heat Flux	Th=482°F (250°C), Tc=122°F (50°C) @matched load	15	16	17	W/cm^2
Mass		69	70	71	g

A=ampere; g=gram; Ω=ohm; V=volt; W=watt, W/cm^2=watts per square centimeter
Source: Hi-Z Technology

Low-temperature ATEGS

To produce the low-temperature ATEGS, the BiTe TEG modules are sandwiched between a water-cooled plate (for removing heat from the module cold side) and fins that are in contact with the waste heat gases (for heating the hot side of the module). In the LTTEG unit, six BiTe TEG modules are arranged in a stack assembly with one cold-side water channel and two hot-side fin assemblies. Figure 5 illustrates the six hot-gas fin stack assembly, which contains corrugated fins with advanced surface features that collect heat from the hot gases and conduct that heat to the hot side of the modules located within the five full and two half cylindrical fairings at the top and bottom of the stack that channels the hot gases. The total power output for this assembly is estimated at 500 We, considering a conservative module output within the system of 14 We.[1] To create systems with higher power output, multiples of the 500-We systems would be utilized. Protruding from the sides of the fairings are inlet and outlet tubes for the cooling water, as illustrated in Figure 5. For a given hot waste heat and cold-water-cooled heat sink temperature, LTTEG unit performance is optimized by reducing the interface gaps and their associated thermal resistance at the hot and cold sides of the TEG modules. To accomplish this objective, a thermal grease (Parker, 2023) is used at the interfaces, and the stack shown in Figure 5 is clamped by tie rods to produce a surface loading of 100 pounds per square inch (psi), or greater, on the modules.

Figure 5: 500 We LTTEG Stack Illustration

Source: Altex Technologies Corporation

To package this stack for installation into an exhaust duct and insulate the stack from heat losses, a sheet-metal box was fabricated to enclose the stack and its insulation. This package also provides structural rigidity to the system. The packaging is shown in Figure 6. Three tie rods in tension, front and back, load the stack. The three front tie rods are visible in Figure 6, as are the wire and water access ports.

[1] Each row in the assembly had six modules (three on each side of the cold-side heat exchanger) and the overall assembly had six rows, or a total of thirty-six modules. It was estimated that each module, when packaged into the assembly, would have an output of 14 watts (W), due to constraints of interfacial thermal resistances. Using 14 W per module, the total power would be 500 W.

Figure 6: Completed and Packaged LTTEG Unit With Side Plates

Source: Altex Technologies Corporation

HTTEG Unit Modules

The HTTEG unit modules are custom developed and manufactured by Hi-Z (Hi-Z Technology, 2023) using segmented PbTe- and BiTe-based semiconductor elements for high exhaust temperature applications, with a preferred hot-side temperature in the range of 932°F (500°C) to 1112°F (600°C). No such TEG module product exists today in the U.S. market.

The HTTEG unit modules are constructed of an array of 10 by 10 semiconductor elements and can typically produce between 20 We to 25 We with a temperature difference (ΔT) of 900°F (500°C) between the hot and cold sides. Six modules can then generate from 120 We to 150 We that, when combined with the 150-We LTTEG unit, can meet the required 250-We high-temperature ATEGS test article. The modules are 72mm by 72mm by 9.5mm thick.

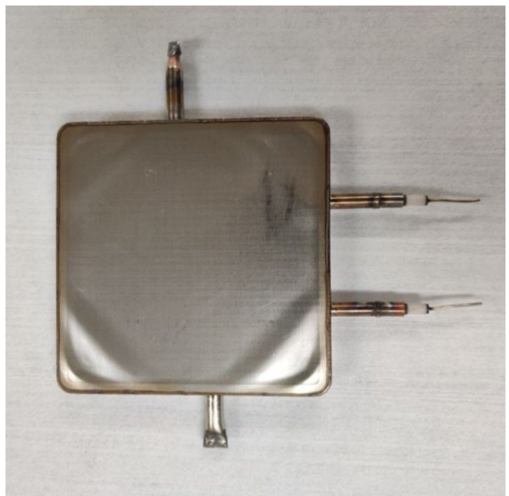
To fabricate an encapsulated HTTEG unit, the major processing steps were to:

(1) Synthesize TEG materials
(2) Make segmented semiconductor elements
(3) Load elements in a grid
(4) Metallize the cold-side
(5) Fill gaps
(6) Flatten the surface

(7) Metallize the hot side
(8) Encapsulate
(9) Test

Figure 7 shows the Hi-Z fully encapsulated and sealed HTTEG unit, with wire leads on the right and the vacuum and gas supply lines on the top and bottom.

Figure 7: Fully Encapsulated and Sealed HTTEG Unit Module: Cold Side (72mm by 72mm by 9.5mm)



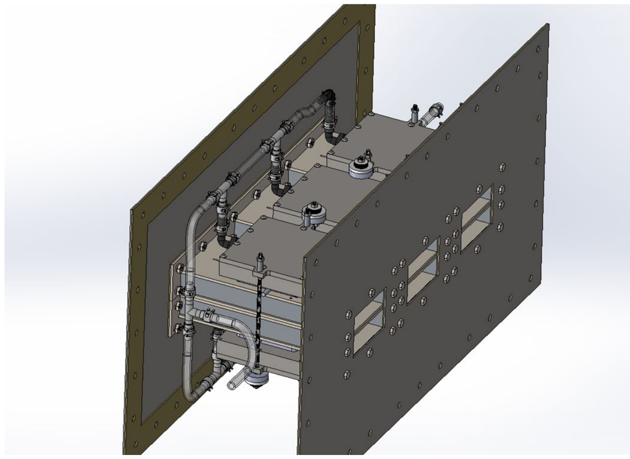
Source: Hi-Z Technology

Six high-temperature TEG modules were produced and delivered for HTTEG unit installation and testing. Throughout the HTTEG development, numerous power generation tests were conducted on TEG modules: a down-sized 4 by 4 mini-module, a non-encapsulated full-size module, and all encapsulated modules. The mini-module was tested for about six months, while the non-encapsulated full-size module was tested for about one week. The mini-module tests utilized a vacuum chamber to avoid component oxidation, while the encapsulated modules were tested in ambient air. In both cases, the modules were loaded to 100 psi and an electric heater was used to heat the hot side to the required temperature; water cooling was used to control the cold-side temperature. These test results demonstrated that the HTTEG unit module technology was successfully developed for this project. All of the delivered modules produced over 20 We of power under planned operating conditions. Details of the individual module test results are shown in the section of this report titled High-temperature ATEGS Tests.

High-temperature ATEGS

The HTTEG subsystem with six Hi-Z TEG modules is illustrated in Figure 8. The six inlets for the high-temperature products of combustion (POC) gas from waste heat sources are shown on the right in Figure 8. The POC flows through corrugated nickel-based fins to transfer heat to the six modules.

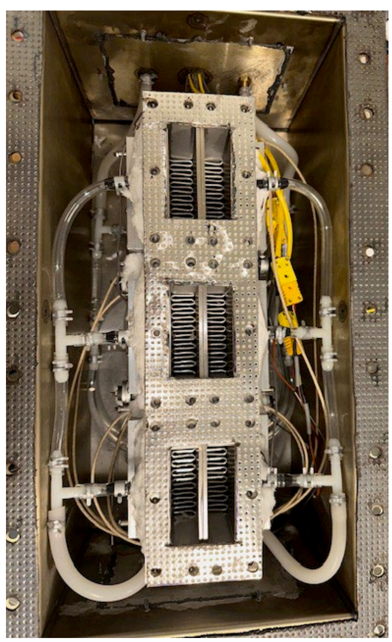
Figure 8: HTTEG Unit Test Article Assembly



Source: Altex Technologies Corporation

Also shown at the top of the hot-gas ducts are three of the six water-cooled heat exchangers with their water supply tubing. These heat exchangers interface with the Hi-Z TEG modules. The heat exchangers and modules are loaded by six tie rods, with one tie rod shown toward the front of the illustration on the side of the assembly. To concentrate the load on the couples within the modules, copper and mica sheets were sandwiched together on the hot and cold sides of the modules. These thin sheets added two significant interface resistances and smaller conductance resistances to each side of the modules. Besides concentrating the load and flexing to remove some gaps, the sheets allowed the modules to be more easily removed for both post-system test analysis and further testing. For production units, the system will not have these extra resistances, so production unit performance is expected to improve. Figure 9 is a photo of the assembled HTTEG unit, ready to be installed in the test boiler.

Figure 9: HTTEG Assembly



Source: Altex Technologies Corporation

Test System

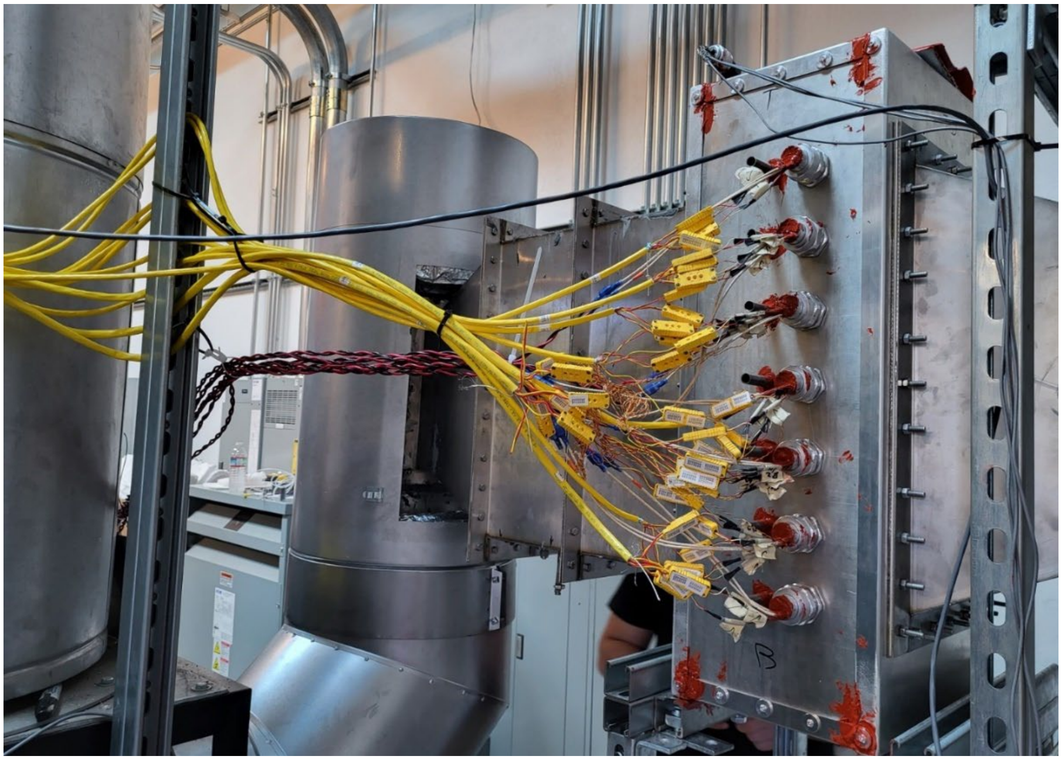
To prepare for unit testing, an 8-MMBtu/hr (metric million British thermal units per hour) test boiler/heater was brought to operational status (the unit is pictured in Figure 10). The boiler/heater has flexible capacity and can provide heat inputs from 2.27 MMBtu/hr to nearly 8 MMBtu/hr. The unit is outfitted with a gas-flow meter and multiple temperature and pressure monitoring instruments for recording performance and safety parameters on a LabView data acquisition system. A National Fire Protection Association-approved and Underwriters Laboratories-certified Fireye control system controls the system.

Figure 10: 8-MMBtu/hr Boiler/Heater Test System

Source: Altex Technologies Corporation

The LTTEG and HTTEG test units are integrated into the boiler/heater exhaust. Through air dilution, the exhaust temperature can be controlled from 500°F (260°C), which is characteristic of the broad population of boilers, up to 1200°F (648°C) to simulate high-waste heat gas temperatures produced by technologies such as gas turbine exhausts and processing furnaces. Figure 11 shows the installed LTTEG test unit in the test system exhaust.

Figure 11: Installed 500 We LTTEG Unit With Wiring and Thermocouple Instrumentation Lines



Source: Altex Technologies Corporation

At the start of a test, the ATEGS water cooling is activated and its operation verified. The boiler is then started and the ATEGS is brought to operating temperature. The ATEGS is initially operated under open circuit voltage conditions to establish that the system is functioning correctly. If proven, the ATEGS circuit is then loaded and the power monitored. All power, flow, pressure, and temperature data are recorded by a LabView program on a dedicated laptop computer for later review and analysis.

Simple Cost Estimations

For the ATEGS to be broadly adopted by industries, it must have a low payback period of fewer than five years. In some cases (such as in government facilities and schools), the payback period can be greater than five years, but it should be fewer than 10 years. The higher the payback, however, the narrower the total market.

The use of waste heat to drive the ATEGS is an important advantage of the system because fuel cost is always a major contributor to the operational costs for a typical energy system. Another ATEGS advantage is water heating, which could support process heating in a facility. The production of useful hot water with the CHP option, which has monetary value, can offset some of the costs of producing ATEGS power, reducing the payback time. To determine payback for the base and CHP ATEGS cases, the capital cost for each case was calculated. Low (LTTEG) and high (HTTEG) temperature waste heat gas cases were considered in the assessment. These cases are described in the sections of this report titled Low-temperature

ATEGS Tests and High-temperature ATEGS Tests, respectively. Results from the simple cost estimation are described in the section of this report titled Simple Cost Estimation Results.

While more complex economic metrics (such as return on investment) could be considered, simple payback is an acceptable metric for first-cut economic assessments. To calculate payback, the equipment capital cost is divided by the net positive revenue generated by either offsetting only grid power to a facility (in the base configuration) or by offsetting both grid power and hot-water production (in the CHP configuration). Equipment capital costs were estimated using the components shown in Figure 6 and Figure 9 that support low- or high-temperature ATEGS, respectively. Based on fabricating LTTEG and HTTEG unit subassemblies and installing them in a commercial boiler in this project, costs for these components are known for very low production volumes. If the ATEGS has acceptable performance and economic metrics, such as under a 5-year payback, then system production volumes would be significant, based on Figure 3 market results. However, the production capacity for both 8-kWe LTTEG and 8-kWe HTTEG units would still be a modest 625 and 438 units per year, respectively. Although fuel cost is not considered for these waste heat cases, parasitic power and annual maintenance costs are included in the operating cost. For the CHP configuration, the earlier purchase and installation costs of a Cain economizer (Cain Industries, 2023) for the test boiler were utilized.

A key cost component of the ATEGS is the low- (LTTEG) and high-temperature (HTTEG) Hi-Z unit production costs. Hi-Z has a well-supported market price for the established LTTEG unit. For its state-of-the-art HTTEG unit, Hi-Z developed an estimated price. At this stage, a low production volume price could be somewhat reduced as production volumes increase. Specifically, Hi-Z estimated higher production costs based on volumes of 250,000 and 175,000 units per year for low- and high-temperature units, respectively. These unit production volumes are consistent with significantly smaller system production volume estimates noted for the 8-kWe size. The low- and high-temperature unit production costs for the 8-kWe size are projected to be \$2/We and \$5/We, respectively; high-temperature unit costs have greater uncertainty. The costs for the 8-kWe LTTEG and HTTEG base and CHP systems are listed in Table 3.

Table 3: Specifications and Costs of ATEGS Base and CHP Components

	LTTEG	LTTEG
Specification	**Base**	**CHP**
Heat (kW)	267	267
Power (kWe)	8	8
Eff (%)	0.03	0.03
Component Cost		
TEG ($)	16,000	16,000
Heat exchangers (HEX) ($)	12,000	12,000
Load ($)	3,200	3,200

	HTTEG	HTTEG
Specification	**Base**	**CHP**
Heat (kW)	160	160
Power (kWe)	8	8
Eff (%)	0.05	0.05
Component Cost		
TEG ($)	40,000	40,000
HEX ($)	7,200	7,200
Load ($)	3,200	3,200

Specification	LTTEG Base	LTTEG CHP
Component Cost		
Housing ($)	2,500	3,500
Electrical ($)	6,200	6,200
Water ($)	5,610	22,440
Assembly ($)	640	960
Total ($)	46,150	64,300
Total $/kWe	5,769	8,038
Installation ($)	8,000	13,000
Total installed cost ($)	54,150	77,300
Total installed cost ($/kWe)	6,769	9,663

Specification	HTTEG Base	HTTEG CHP
Component Cost		
Housing ($)	2,500	3,500
Electrical ($)	6,200	6,200
Water ($)	3,400	13,600
Assembly ($)	640	960
Total ($)	63,140	74,660
Total $/kWe	7,893	9,333
Installation ($)	8,000	13,000
Total installed cost ($)	71,140	87,660
Total installed cost ($/kWe)	8,893	10,958

HEX=heat exchanger; kW=kilowatt; kWe=kilowatt electric
Source: Altex Technologies Corporation and Hi-Z Technology

The hot-side heat exchanger is custom designed to fit the TEG modules and interface with the hot waste heat. For the low-temperature case, the heat exchanger fins were fabricated from aluminum, which has very good thermal characteristics and is much lower in cost than copper. This type of heat exchanger has been fabricated at different scales, and costs from these developments were used to estimate the LTTEG hot-side heat exchanger cost of $45/kW (Kelly, 2016). For the cold side, the heat exchanger is also constructed of aluminum and, due to the high-heat conductivity of water, this heat exchanger is very compact. These types of heat exchangers are well developed, and costs are well defined. The estimated cost for these cold-side heat exchangers is $21/kW. To load the units and reduce thermal resistances, a simple tie-rod mechanism with cross beams on the top is used. In this project, multiple loading mechanisms were developed and utilized. Given the production volumes of 625 units/year, the cost per loading mechanism for an 8-kWe system is $3,200. Electric power conditioning to convert the TEG-generated direct current (DC) to higher voltage alternating current (AC) is based on readily available solar power equipment. The cost of this equipment for an 8-kWe power ATEGS is $6,200 (ABB Group, 2023).

To integrate with hot exhaust gases, the LTTEG unit must be contained in an insulated housing such as that shown in Figure 6 and Figure 9. Based on low-volume production cost quotes, a higher unit production cost was estimated. The results are shown in Table 3. To get the total subsystem cost, an assembly cost of $640 was estimated, based on higher production volumes and well-trained and experienced assemblers. Totaling component and assembly costs, total costs for the LTTEG can be estimated, as shown in Table 3.

For the higher-temperature HTTEG unit, more heat-resistant heat exchangers (HEX in Table 3) are required. A nickel-based alloy provided this required heat resistance. The material can withstand high operating temperatures over a long time period without degradation or failure.

This material has a significantly higher cost than the materials used in the low-temperature LTTEG. Based on the development and use of these materials in other high temperature applications, the cost is an estimated $51/kW, as shown in Table 3.[2] In addition to improved materials used in the HTTEG heat exchangers, more heat-resistant but low-cost materials are used in the subsystem housing. In this case, the housing cost is estimated and, ultimately, the total cost for the HTTEG can be estimated, also shown in Table 3.[3] Lastly, a Cain economizer (Cain Industries, 2023) has been integrated into the boiler for hot-water upgrading, and the costs for these systems are well known. Using the known costs, the costs for LTTEG and HTTEG base units and LTTEG and HTTEG CHP units are estimated, and the results are shown in Table 3. These results show that the TEG costs for the LTTEG systems are 34.7 percent and 24.9 percent of the base and the CHP uninstalled system costs, respectively. For the HTTEG systems, the base and CHP TEG costs are 63.4 percent and 53.6 percent, respectively, which represent the major HTTEG cost.

The results in Table 3 form the foundation for simple payback estimates. To estimate simple payback, the capital cost is divided by the net revenue (including the values of power and hot water in the CHP cases) per year. Since the waste heat cost is zero, the net revenue must subtract only maintenance costs and parasitic power from the combined power and hot water revenue included for CHP. Results of these simple payback calculations are provided in the section of this report titled Simple Cost Estimation Results.

[2] In Table 3, the higher quality material HTTEG HEX is less expensive than the aluminum material LTTEG HEX, because the HTTEG module has almost twice the efficiency of the LTTEG modules and, for the same power output, the HTTEG HEX heat input is about 50 percent lower. This reduction in heat management and HEX volume, weight, and cost offsets the higher material costs for the HTTEG HEX.

[3] The HTTEG would have a higher temperature resistant insulating liner with some stainless-steel components. Therefore, material costs would be somewhat higher, but the overall HTTEG housing would be smaller. Also, fabrication costs are significant and tend to reduce the impact of material costs on the overall component cost. To be conservative at this early stage, the team assumed the costs would be equal, given that even a 20-percent change in this housing cost results in only a 0.05-year change in simple payback. This impact is trivial, given all of the other factors impacting payback. Therefore, the team's recommendation is to let these housing costs be equal in Table 4.

CHAPTER 3: Results

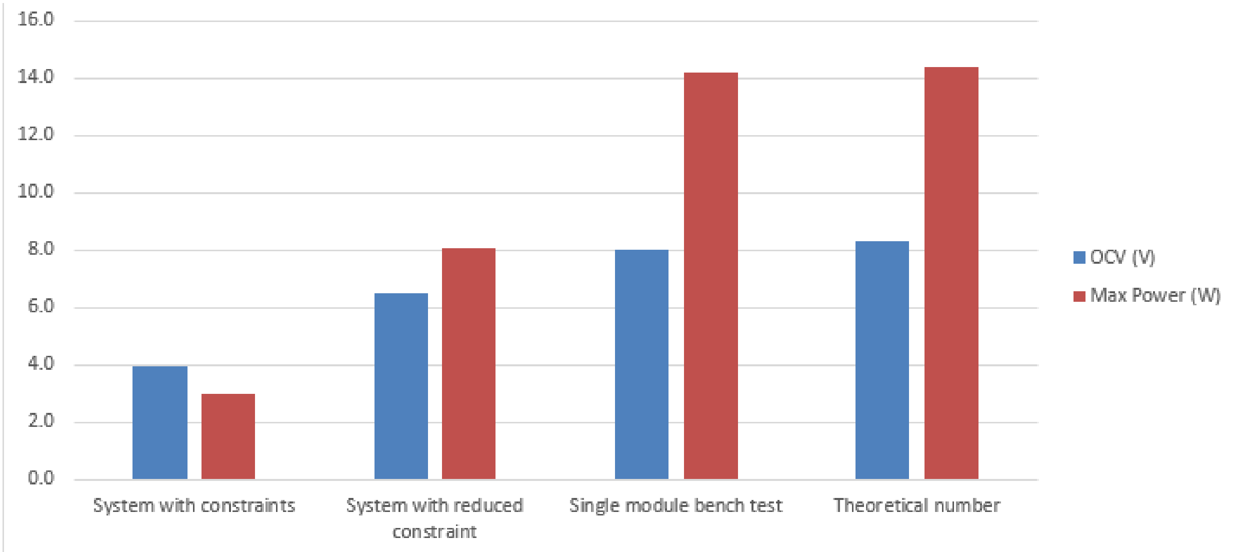
Low-temperature ATEGS Tests

Using Hi-Z's commercial BiTe TEG modules with cold-side water cooling and fin-based hot-side gas heating of temperatures up to 500°F (260°C), the 500-We LTTEG unit was installed in the 8-MMBtu/hr test boiler exhaust (Figure 11). The boiler was then brought to operating condition and the LTTEG unit was tested. Initial tests showed that the unit was producing only 3 We per TEG module; the expectation was production of over 10 We per module under similar temperature conditions. A root cause analysis was conducted, along with bench-top tests of sub-components; these indicated that the stack had excessive unit loading constraints due to the packaging of the stack. To demonstrate that these constraints were limiting the performance of the LTTEG unit, the water line pass-throughs and shell constraints were relieved and the LTTEG unit was retested. At temperatures similar to the initial tests, the modules produced an average of 8 We, or an improvement of approximately 167 percent. This clearly showed the impact of constraints on unit loading and power output. This loading is very important for achieving good contacts between the unit and the fins that transfer heat to the unit on the hot side, away from the water-cooled heat exchangers on the cold side. If the thermal resistance is high due to air gaps or lack of thermal grease for filling gaps, then LTTEG performance will be compromised.

The ideal performance for the unit is roughly 14 We for the temperature conditions measured in the tests, but this assumes that the interface thermal resistance is low and that the temperatures are imposed on the unit. With the initial LTTEG unit (with constraints), the loading was partially distributed to the constraints; the surface contact was limited, so the interface thermal resistances were high between the unit and the hot- and cold-side heat exchangers.

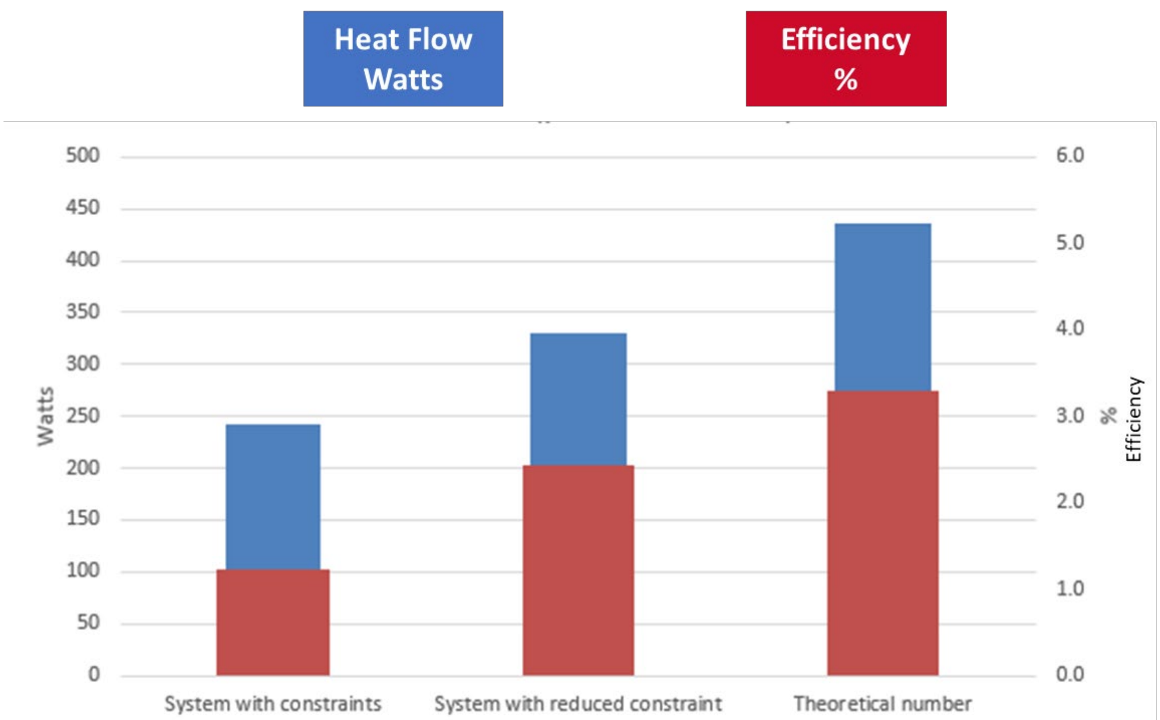
As the constraints on module loading were reduced in the final low-temperature ATEGS test, the open circuit voltage (OCV), power and the efficiency performance began to approach both the single TEG module test results and the theoretical model results. These results are shown in Figure 12 and Figure 13. As shown in Figure 12, the single module test OCV and the power results are close to the Hi-Z theoretical-module model results. The updated system with reduced constraints shows the OCV is within 20 percent of the single module test results, which is a significant improvement over the initial system test results with constraints. However, the updated system power output is still significantly below the single module test results. This is likely due to remaining interface thermal resistances that limit heat flow and power output. This suggestion is supported by the results in Figure 13, which shows the shortfall in heat flow for the updated system versus the model results. The heat flow was calculated using measurements of the rise in the cooling-water temperature and the water flow rate. The shortfall in power also results in a lower efficiency, which is also illustrated by the updated system data versus the model results.

Figure 12: Comparison of LTTEG Unit OCV and Power Test Results Versus Single Module Test Results and Model Results



Source: Altex Technologies Corporation

Figure 13: Comparison of LTTEG Unit Heat Flow and Efficiency Test and Model Results for Each Module



Source: Altex Technologies Corporation

From these test results, it can be concluded that TEG unit loading and good surface contacts are key areas for reducing interface thermal resistance and achieving performance more in line with module specifications. While the performance with the reduced constraints was much improved, it was still short of ideal. Given the importance of interface thermal resistance to performance, it is speculated that surface flatness and roughness, combined with the hardening of thermal grease (ahead of testing), probably contributed to higher interface thermal resistance and performance reductions relative to single TEG module test results.

High-temperature ATEGS Tests

Using Hi-Z's PbTe high-temperature TEG modules with cold-side water cooling and fin-based hot-side gas heating, the HTTEG unit was installed along with the lower-temperature LTTEG unit in the 8-MMBtu/hr test boiler exhaust. Considering the lessons learned from the LTTEG packaging, the HTTEG design minimized packaging constraints when loading the units. As shown in Figure 8, separate cooling elements were used on each stack for separate and independent loading of the TEG modules. However, the high temperature of the operation for HTTEG prevented thermal grease use on the hot side to compensate for the imperfect interfacial contact. The boiler was then brought to operating condition and the combined HTTEG and LTTEG units were tested. Initial tests showed that the HTTEG unit was producing up to 9.1 We per TEG module, where the expectation was the production of approximately 20 We per module for hot-side module temperature conditions of 1040°F (560°C). The expected cold-side temperatures were in the range of approximately 113°F (45°C), indicating that the water cooling was performing as anticipated. However, the HTTEG unit temperature of up to 914°F (490°C) was lower than the TEG module surface target temperature of 1040°F (560°C), due to limitations in the boiler test system. The original demonstration test was planned at a pet crematorium that could achieve a high gas temperature of 1472°F (800°C), as determined by onsite gas temperature measurements. Due to changes in business plans at the pet crematorium, the demonstration tests were shifted to the modified 8-MMBtu/hr boiler at the researchers' test site. This boiler is well suited for the LTTEG unit tests that require only 500°F (260°C) exhaust-gas waste heat temperatures. Through exhaust modifications, it was projected that exhaust temperatures suitable for the HTTEG demonstration testing could be achieved. Unfortunately, the system could not reliably achieve the needed temperatures and could reach only 1076°F (580°C) versus the desired 1220°F (660°C), which could have been provided by the crematorium. This shortfall in temperature compromised the HTTEG unit performance.

Aside from the hot-temperature impacts on reducing performance, it was also possible that the TEG modules were damaged during installation or were degraded by testing in the HTTEG unit. To assess these possibilities and their impacts on performance, the TEG modules were removed from the unit following testing and were retested as single modules on a bench-scale test apparatus at Hi-Z's facility, which was previously used for single module tests.

Prior to performance testing of the TEG modules at Hi-Z, surface conditions and interface materials in the HTTEG unit were inspected to assess hot-side contacts. From the different coloration of the copper-separation sheet surface, it appeared that the interface contact was not uniform over the surface, with some areas remaining relatively unoxidized (copper color) and others showing some oxidation (darker areas that were likely copper oxide), indicating air penetration into gaps. A similarity was observed for the mica separation sheet, where the center had a gray color versus the surrounding area. The dark areas on the mica sheets also show that the sheets and TEG module alignment were not perfect and that some areas may not have made good contact with the modules. While not quantitative, these images suggested that interfacial contact was not uniform and that module-to-interfacial sheet alignment was not perfect during the HTTEG unit tests. These non-ideal interface characteristics could have also contributed to the shortfall in performance of the HTTEG unit versus the single TEG module performance.

Following the original single module test procedure, the six HTTEG units were retested. These tests ramped up the module hot-side temperature from 393°F (200°C) to 1130°F (610°C) over a day, then held the module at that peak temperature overnight before ramping down the temperature to 393°F (200°C) the next day. With this procedure, the module performance, as a function of temperature, could be determined over one up-and-down cycle to see if short-term degradation occurred.

The power generation test results of all six encapsulated HTTEG units are shown in Table 4. Most modules generated power around 24 We at the ∆T of ~ 1058°F (570°C), or around 21 W with the ∆T of ~ 959°F (515°C). Considering significant temperature drops across the thermal interfaces on both the hot and the cold sides, the real ∆T applied to the unit (hot-side metallization to cold-side metallization) is estimated to be about 932°F (500°C) for the two cases referenced here.

Table 4: Hi-Z Test Results of Encapsulated HTTEG Unit Modules

Unit #		Heater	Heatsink	OpenCircuit	Module Internal	Power Output
Hi-Z	Researchers	Temperature (ºC)	Temperature (ºC)	Voltage (OCV)	Resistance (Ω)	(W)
1	6	196.7	31.5	2.17	0.79	1.50
		296.7	34.4	3.78	0.77	4.65
		399.1	37.6	5.65	0.83	9.64
		503.5	40.8	7.68	0.94	15.68
		556.1	42.2	8.69	1.01	18.76
		609.1	42.9	9.74	1.10	21.63
2	5	196.1	28.3	2.20	0.49	2.46
		296.0	31.6	3.82	0.57	6.36
		398.4	34.8	5.74	0.70	11.83
		502.7	37.9	7.80	0.84	18.16
		555.2	39.5	8.82	0.91	21.45
		608.6	40.9	9.84	0.99	24.58
3	1	196.6	26.3	2.19	0.50	2.39
		297.1	29.1	3.83	0.59	6.18
		399.6	31.9	5.70	0.71	11.47
		504.0	35.2	7.74	0.85	17.58

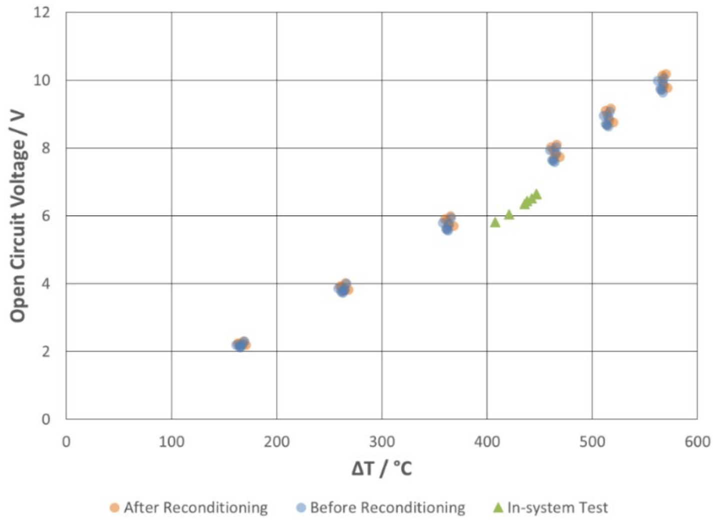
Unit #		Heater	Heatsink	OpenCircuit	Module Internal	Power Output
Hi-Z	Researchers	Temperature (ºC)	Temperature (ºC)	Voltage (OCV)	Resistance (Ω)	(W)
		556.9	37.0	8.75	0.92	20.77
		609.9	38.6	9.78	1.01	23.61
4	2	196.4	33.8	2.24	0.53	2.38
		296.3	36.2	3.94	0.61	6.32
		398.6	39.1	5.91	0.74	11.78
		502.6	42.1	8.03	0.89	18.07
		555.5	43.3	9.11	0.97	21.40
		608.6	42.3	10.15	1.04	24.76
5	3	195.9	31.7	2.23	0.51	2.42
		295.7	34.5	3.91	0.59	6.43
		398.6	37.2	5.86	0.71	12.07
		502.9	39.9	7.92	0.85	18.53
		555.1	41.3	8.99	0.93	21.80
		608.6	42.6	9.98	1.00	24.98
6	4	196.3	28.3	2.31	0.58	2.32
		296.4	31.2	4.03	0.64	6.30
		398.9	34.0	5.99	0.76	11.82
		502.8	36.8	8.11	0.91	18.09
		555.2	38.1	9.18	0.99	21.29
		608.7	38.8	10.18	1.07	24.25

Source: Hi-Z Technology

During the short-term degradation test, the OCV, electrical resistance, and power output were recorded, along with the heater power input and water cooling. These results confirmed that the TEG modules were neither degraded nor damaged during installation and system testing. It should be noted that the difference in interfacial layers with the retested modules did lead to a small performance difference, which was expected. It was then concluded that the primary difference between the HTTEG and the single TEG module results was related to module temperature differences and interface resistances impacted by surface conditions and loading.

Figure 14 compares the OCV results of the HTTEG unit test and the single TEG module retest for the six modules versus the ΔT between the hot-side and water-cooling temperatures. The ΔT was used in these comparisons because the TEG performance was driven by the ΔT, not just the hot-side temperature. As shown, the OCV measurements are not appreciably different over the range of measured temperatures.

Figure 14: OCV Comparison of HTTEG Unit and Single TEG Module Retest



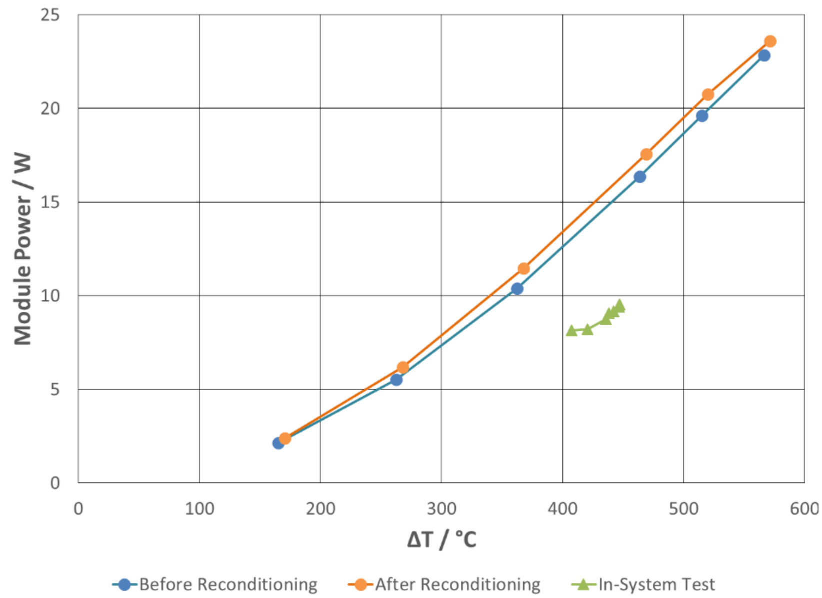
Source: Altex Technologies Corporation and Hi-Z Technology

This correspondence supports the conclusion that the TEG modules within the HTTEG unit were producing OCV levels similar to those measured for the single module.

Figure 15 compares the power produced for an HTTEG unit with six single TEG module measurements versus the ΔT between the hot-side and water-cooling temperatures. As shown, the HTTEG unit power is 60 percent to 63 percent of the single module power recorded at the highest ΔT measured. This is in marked contrast to the similarity of the OCV results. These differences are a result of how the unit generates OCV and power. When OCV is measured, no current is flowing through the unit and, for the given ΔT, a voltage will be created. This is a process similar to how a thermocouple measures temperature. When current flows through an external load, the internal thermal resistance and the heat flow are altered. When current is flowing, the total amount of current is controlled to some extent by the contact areas and the thermal resistances in the separating layers, and by the interfaces. If local interface resistances are higher, or if contact areas are lower, power will be reduced. Given the complexity of the interface flatness and roughness, and the clamping load for multiple layers in the HTTEG unit, it is difficult to assign power reductions to a specific layer or layer interfaces. However, from the LTTEG unit testing described in the validation test report (Kelly, 2023), it can be concluded that these effects could potentially reduce power output when compared with the well-controlled single TEG module tests.

While various specific layer contributions cannot be identified at this time, the differences in the power measured, shown in Figure 15, could be associated with a global contact area reduction. Using this approach, it is estimated that the HTTEG unit contact area was reduced by 37 percent to 40 percent versus that of the single module tests. If changes in resistances and their impacts are considered, then this reduction in effective surface area would be less. To improve HTTEG unit power to the level experienced with the single module tests, it will be important to reduce surface roughness (and deviations from flatness) and improve both clamping uniformity and load. Through these refinements, HTTEG system power output for a given temperature could be increased to levels experienced in the single module tests.

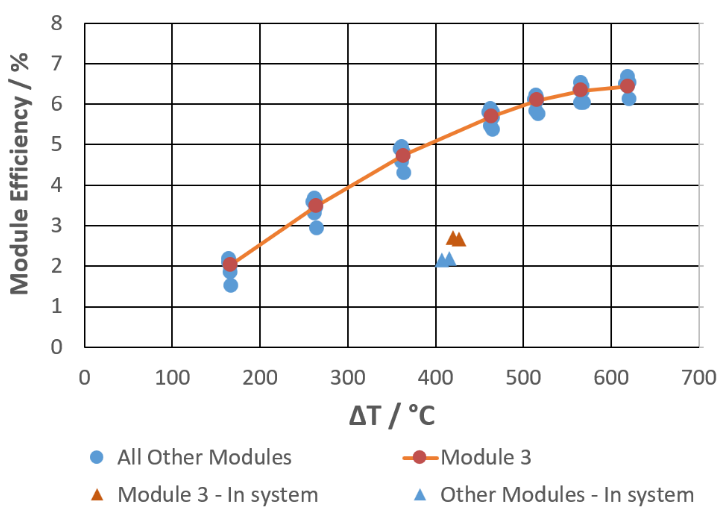
Figure 15: Comparison of HTTEG Unit and Single TEG Module Retest Power Outputs



Source: Altex Technologies Corporation and Hi-Z Technology

Another important performance parameter is efficiency. The six single TEG module retest results shown in Figure 16 show that all modules exceeded the 5-percent efficiency project target at the ΔT of interest. Using the sum of the heat absorbed by the water and the generated electrical power as the heat input into the modules, the HTTEG unit efficiency was calculated at 2.7 percent. This reduction in system efficiency is a direct result of the shortfall in power for the HTTEG system due to the reasons just described. With higher temperatures and an improvement in power output at a given temperature, the HTTEG unit will exceed 5-percent efficiency. As shown in Figure 16, single module efficiencies of up to 6.5 percent were achieved. This is a noteworthy accomplishment of this project.

Figure 16: Comparison of HTTEG Unit In-System and Single TEG Module Retest Energy Efficiency



Source: Altex Technologies Corporation and Hi-Z Technology

Simple Cost Estimation Results

An important project metric for the ATEGS was to achieve a simple payback of under 5 years. As described in the section of this report titled Simple Cost Estimations, the simple payback is equal to the capital costs (including site installation), divided by the net positive revenue from operating the ATEGS over a year (including replacement of grid power and the generation of hot-process water for the CHP option). While the values of power and hot water vary over time, the simple payback calculation uses current fixed grid power and fossil gas prices. These prices have substantially increased during the past three years due to multiple global factors and high inflation. Table 5 gives the California commercial and industrial fossil gas and prices for February 2022 and February 2023 (IEA, 2023).

Table 5: California Power and Fossil Gas Prices for Commercial and Industrial Customers

Date	Power ($/kWh) Commercial	Power ($/kWh) Industrial	Fossil Gas ($/MMBtu) Commercial	Fossil Gas ($/MMBtu) Industrial
February 2023	0.214	0.195	23.89	19.35
February 2022	0.159	0.141	18.82	16.94

Source: IEA, 2023

These prices are substantially above historical prices, which will make waste-heat-driven systems like the ATEGS more viable economically. Given the significant recent variability in power and fossil gas prices both over a year and on a year-to-year basis, reasonable selected power and fossil gas prices are $0.20/kWh and $22/MMBtu, respectively. Table 3 and Table 6 list different ATEGS options and their associated capital costs and net revenues. ATEGS are expected to operate 8,000 hours per year, which maximizes net revenue and minimizes payback. If the system is operated for half this time per year, the payback time would roughly double. As shown in Table 6, the base LTTEG and HTTEG cases have a 4.77-year and a 6.27-year payback, respectively. Therefore, at these power and fuel prices, the LTTEG meets the under-5-year payback project goal. While the HTTEG has a payback above that goal, a reduction in module cost from $5/We to $3.2/We would allow the base HTTEG to meet the project goal. With improvements in manufacturing and an increase in production volumes, it may be possible to reduce module costs to near $3.2/We. However, even without this reduction, some customers would accept the 6.27-year payback time. For the LTTEG and the HTTEG CHP cases, the paybacks are 0.56 year and 1.00 year, respectively. Of course, in these cases, the hot water must be fully used in the facility. If the hot water is used for the process only 50 percent of the time, the paybacks for the LTTEG and the HTTEG are 1.12 years and 2.00 years, respectively. These are still excellent paybacks and indicate that LTTEG and HTTEG hot-water use can be only a fraction of the time and systems will still meet the 5-year payback goal.

As noted earlier, California's waste heat market is substantial; it is possible that other waste heat technology will ultimately compete with the ATEGS. Many sites will also avoid modifications to eliminate capital needs and instead maintain a focus on low-risk production.

Given these factors and the substantial uncertainties in the fuel market, a market deployment of 20 percent is assumed. Given the individual unit cost savings listed in Table 6, and the 20 percent deployment in the full market of 6,250 LTTEG and 4,375 HTTEG units, the total ATEGS cost savings are listed in Table 7. The second line in Table 7 gives the full deployment cost to industry users if each LTTEG and HTTEG base or CHP system were deployed at the assumed 20-percent share of the under 600°F (316°C) and the 600°F (316°C) to 1,000°F (538°C) waste heat markets, as described in the section of this report titled ATEGS Potential Markets. Specifically, 6,250 units and 4,375 units would be deployed in the under 600°F (316°C) and the 600°F (316°C) to 1,000°F (538°C) waste heat markets, respectively.

Table 6: Simple Payback for LTTEG and HTTEG Base and CHP Options

Specification	LTTEG Base	LTTEG CHP
Generated (kWh)	6,765	56,765
Hot Water (MMBtu/yr)		6,378
Fuel Price ($/MMBtu)		22
Hot Water ($/yr)		126,288
Power Price ($/kWh)	0.2	0.2
Power ($/yr)	11,353	11,353
Total ($/yr)	11,353	137,642
Total Installed Cost (Table 3) ($)	54,150	77,300
Payback (yr)	4.77	0.56

Specification	HTTEG Base	HTTEG CHP
Generated (kWh)	56,764.8	56,764.8
Hot Water (MMBtu/yr)		3,827
Fuel Price ($/MMBtu)		22
Hot Water ($/yr)		75,773
Power Price ($/kWh)	0.2	0.2
Power ($/yr)	11,353	11,353
Total ($/yr)	11,353	87,126
Total Installed Cost (Table 3) ($)	71,140	87,660
Payback (yr)	6.27	1.00

kW=kilowatt; kWh=kilowatt-hour; MMBtu=metric million British thermal unit; MMBtu/yr=metric million British thermal units per year; yr=year
Source: Altex Technologies Corporation

Table 7: Total ATEGS Cost Savings for 20-percent Deployment in Total Market

	LTTEG Base	LTTEG CHP	HTTEG Base	HTTEG CHP	Total Base	Total CHP
Savings/Year ($MM)	71	832	50	361	121	1,193
Full Deployment Cost ($MM)	338	483	311	384	649	867

Source: Altex Technologies Corporation

To be conservative in the above economic calculations, the over-20-percent federal tax credit for waste heat recovery systems was not considered. This tax credit is not permanent, and its economic impact depends on the tax situation of the company investing in the waste heat recovery system. Nevertheless, these federal and state credits can be an additional economic driver to promote deployment of ATEGS waste heat recovery systems.

To illustrate the impact of power and fossil gas prices on payback, Table 8 provides paybacks for a range of power and fossil gas prices. As shown, as the power price is reduced, the base

LTTEG and HTTEG paybacks exceed the under-5-year target. However, the LTTEG and the HTTEG CHP cases have significantly lower paybacks than the under-5-year target over all of the power and fossil gas prices considered. The last line in the LTTEG and HTTEG table shows the payback using the most reasonable estimated power and fossil gas prices. Besides meeting the project payback target, a condensing heat exchanger in the CHP cases will also meet the over-80-percent waste heat recovery project target.

Table 8: LTTEG (Left) and HTTEG (Right) Payback Variation With Power and Fossil Gas Prices

Power	Fuel	Base	CHP
Price	Price	Payback	Payback
$/kWh	$/MMBtu	Years	Years
0.12	10	7.95	1.2
0.14	10	6.81	1.2
0.16	10	5.96	1.2
0.18	10	5.3	1.2
0.2	10	4.77	1.2
0.16	6	5.96	1.87
0.16	8	5.96	1.47
0.16	10	5.96	1.2
0.16	12	5.96	1.02
0.16	14	5.96	0.89
0.2	22	4.77	0.56

Power	Fuel	Base	CHP
Price	Price	Payback	Payback
$/kWh	$/MMBtu	Years	Years
0.12	10	10.44	2.12
0.14	10	8.95	2.12
0.16	10	7.83	2.12
0.18	10	6.96	2.12
0.2	10	6.27	2.12
0.16	6	7.83	3.19
0.16	8	7.83	2.55
0.16	10	7.83	2.12
0.16	12	7.83	1.82
0.16	14	7.83	1.59
0.2	22	6.27	1.00

kWh=kilowatt-hour; MMBtu=metric million British thermal unit
Source: Altex Technologies Corporation

As a result of reducing grid power and fossil gas fuel use at the site, both LTTEG and HTTEG units will reduce criteria pollutants and GHG emissions at the site and at the grid power plant. Using the results in Table 6 and established criteria pollutant and GHG factors at both the site and the grid, the reductions per year can be estimated for both a single unit and for deployment of 6,250 and 4,375 LTTEG and HTTEG units, respectively. These results are listed in Table 9. As shown, 20-percent deployment of ATEGS in the total market will significantly reduce nitrogen oxide (NOx) criteria pollutants and carbon dioxide (CO_2) greenhouse gases in California.

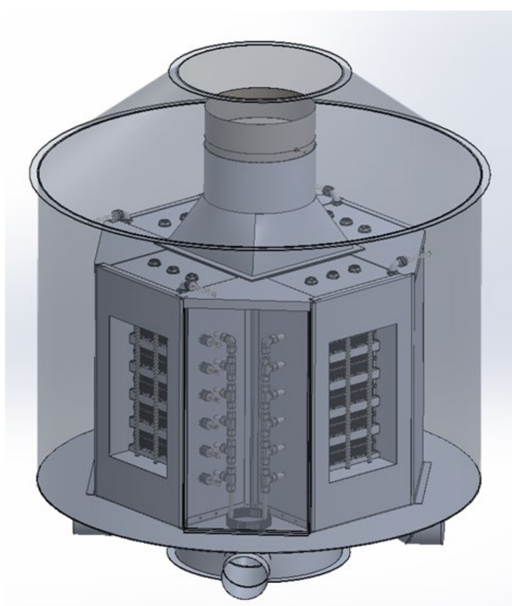
Table 9: Annual Environmental Benefits of ATEGS

	LTTEG Base	LTTEG CHP	HTTEG Base	HTTEG CHP	Total Base	Total CHP
Emissions per Unit						
NOx (Tons/Year)	0.00315	0.0287	0.00315	0.0287		
CO_2 (Tons/Year)	24.0	398.0	24.0	248.0		
Emissions for All Units						
NOx (Tons/Year)	4.53	180.9	13.7	81.6	33.2	262.5
CO_2 (Tons/Year)	150,000	2,487,500	105,000	1,085,000	255,000	3,572,500

Source: Altex Technologies Corporation

The LTTEG and HTTEG units and their associated TEG modules are expected to have lifetimes of over 10 years, as long as temperatures are maintained within their respective limits of 260°C and 560°C, per Hi-Z's recommendations. However, at the high temperatures, the maximum power output will decline by a few percent over the 10-year period. Therefore, the systems should be oversized to make sure the needed power is available by the 10-year milestone. Relative to footprint, the subsystems shown in Figure 6 and Figure 9 can be configured into panels and integrated into an exhaust economizer-type configuration (ABB Group, 2023) and integrated with the waste heat exhaust, as shown in Figure 17. For comparison, a conventional Cain waste heat economizer is shown in Figure 18. The consistency of these two configurations supports the idea that the LTTEG or the HTTEG could be installed in any system where a conventional waste heat economizer could be installed.

Figure 17: LTTEG or HTTEG Waste Heat Economizer Type Configuration



Source: Altex Technologies Corporation

Figure 18: Cain Waste Heat Economizer Configuration for Boilers

Source: Cain Industries

CHAPTER 4: Conclusion

General Overview and Key Implications

Both low- and high-temperature waste heat ATEGS were developed and tested under this project. The low-temperature ATEGS, called LTTEG, is compatible with a large market of boilers and heaters. Power outputs of single TEG modules are approximately 20 We at the optimum hot-side temperature. However, the LTTEG unit showed a significant reduction in power per TEG module during testing in an 8-MMBtu/hr boiler exhaust. Test results concluded that proper unit loading and good surface contacts between components are keys to reducing interface thermal resistance and achieving performance more in line with single TEG module specifications. Given the importance of interface thermal resistance to performance, it is speculated that surface flatness and roughness, combined with the hardening of thermal grease ahead of module loading and testing, probably contributed to higher interface thermal resistance and performance reductions. These test article limitations need to be corrected for future commercial products by grinding the interface surfaces to the required flatness and minimizing roughness and by using fresh thermal grease for the low-temperature interfaces.

The HTTEG test unit was fabricated and installed with the lower-temperature LTTEG unit in the 8-MMBtu/hr test boiler exhaust. Exhaust-gas temperature limitations reduced power output for the HTTEG to less than 10 We per TEG module. A comparison of OCV between the HTTEG installed unit and a single TEG module showed a maximum OCV difference of 14 percent over the temperature range measured for both cases. To improve HTTEG power output and reach the 20-We target, it would be important to increase the HTTEG inlet gas temperature and raise the hot-side module temperature to over 1040°F (560°C). The next important steps would be to reduce surface roughness and flatness to less than 64 micro inches and 0.001 inch/inch, respectively, and to optimize clamping force level and uniformity to minimize interface thermal resistances (Boyd, 2020). If this is achieved, performances for the HTTEG unit will approach those achieved in the single TEG module tests.

Using the test article component costs as a base, the capital costs for 8-kWe LTTEG and HTTEG waste heat driven systems were determined. For current California power and fossil gas prices, the LTTEG and the HTTEG had paybacks of 4.77 years and 6.27 years, respectively. Therefore, the base LTTEG meets the under-5-year project payback target, with the HTTEG relatively close. Reducing the HTTEG module cost would reduce that 6.27-year payback to the 5-year target. The LTTEG and HTTEG CHP options have very favorable paybacks at 0.56 year and 1.00 year, respectively, which are far below the project's upper-limit target of 5 years. This shows that the CHP system operating time per year can be reduced by a factor of five before payback exceeds the 5-year project target. Also, with the use of a condensing heat exchanger, the CHP options can recover over 80 percent of the waste heat, which meets the project goal.

Besides reducing fuel use and fuel cost, deployment of LTTEG and HTTEG units for lower- and higher-temperature exhaust temperature applications will reduce NOx criteria pollutants and CO_2 greenhouse gases. The NOx reductions are 33.2 tons per year and 262.5 tons per year for base and CHP ATEGS, respectively, and 255,000 tons per year and 3,572,500 tons per year CO_2 reductions for base and CHP ATEGS, respectively. The estimated CO_2 reductions exceed the project target.

Benefits and Contributions to California's Clean Energy and Climate Goals

This project shows promise of ratepayer benefits of greater electricity reliability, lower costs, and increased safety. The ATEGS can decrease reliance on the grid by providing onsite electric power, improving thermal efficiency and fuel use in the CHP mode, and reducing facility operational costs, GHGs, and other criteria pollutants. Cooling water from the system can be further heated, using the remaining waste heat gases, and used for hot water needs at commercial or industrial sites, thereby expanding the benefits of the system beyond power generation. These benefits are essential to Assembly Bill 32 for making cost-effective waste heat available to power systems and for distributed generation for California industries.

Next Steps and Future Areas of Research

The cost analysis concluded that the ATEGS is cost effective and environmentally beneficial for low-temperature waste heat and low- and high-waste heat temperatures if the CHP option is used. However, while the potential is clear, the test systems and the project overall had some challenges that must be resolved in production systems to realize the full potential of the ATEGS. For example, the system interface thermal resistances were excessive when compared with single modules. To correct this problem and optimize performance, the heat exchanger and module interfaces must have smooth surfaces, with a surface roughness below 64 micro inches, flatness below 0.001 inch/inch, and uniform component loading. This can be accomplished by machining the surfaces following braze bonding using available grinding equipment. With this surface condition improvement, performance and costs will improve. Relative to production readiness, with better tolerance on interface roughness and flatness, the heat exchanger and packaging components are nearly ready for manufacturing. Other challenges were from COVID-19-related disruptions and from the loss of the host site, which contributed to schedule delays for the ATEGS testing. Therefore, in the absence of available test data, ATEGS publications were neither prepared nor presented at conferences.

The low-temperature modules are currently being manufactured at low-production volumes. A significant investment in manufacturing tooling and equipment will be important to further reduce module costs. The high-temperature modules are state-of-the-art, and more research into refinement of materials and fabrication processes and testing of long-term durability are needed to demonstrate the cost-effectiveness and durability of these modules. Once this effort is completed, an investment would be required in the manufacturing tooling and equipment to increase production throughput and decrease module costs. These efforts could be completed within three years of startup.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
~	approximately equal to
Ω	ohm
A	ampere
AC	alternating current
ATEGS	Advanced Thermo-electric Generator System
BiTe	bismuth telluride
°C	degrees Celsius
CHP	combined heat and power
CO_2	carbon dioxide
DC	direct current
°F	degrees Fahrenheit
g	gram
GHG	greenhouse gas
HEX	heat exchanger
HTTEG	high-temperature thermo-electric generator
HV	high voltage
IEA	International Energy Agency
kW	kilowatt
kWe	kilowatt electric
kWh	Kilowatt-hour
LTTEG	low-temperature thermo-electric generator
mm	millimeter
MMBtu	metric million British thermal unit
MMBtu/hr	metric million British thermal unit per hour
MMBtu/yr	metric million British thermal unit per year
Mwe	megawatt electric
NOx	nitrogen oxide
OCV	open circuit voltage
PbTe	lead telluride
POC	products of combustion
psi	pounds per square inch

Term	Definition
semiconductor thermo-electric material	material that partially conducts electricity and has the capability of converting heat into electricity
ΔT	temperature difference
TEG	thermo-electric generator
V	volt
W	watt
W/cm^2	watts per square centimeter
We	watt electric
yr	year

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Project Deliverables

- Critical Project Review Report
- Final Report
- Final Presentation Materials
- TAC Meeting Summaries
- Design Report
- Fabrication Report
- System Validation Test Plan
- System Validation Report
- Field Demonstration Test Plan
- Field Demonstration Report
- Kickoff Meeting Benefits Questionnaire
- Midterm Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Initial Fact Sheet
- Final Fact Sheet
- Final Production Readiness Plan
- Technology/Knowledge Transfer Plan
- Technology/Knowledge Transfer Report

Project deliverables are available upon request by submitting an email to pubs@energy.ca.gov.